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TECHNICAL NOTE

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PAYLOAD VIBRATION DATA MEASURED DURING FIVE FLIGHTS OF A TWO-STAGE SOLID-PROPELLANT LAUNCH VEHICLE

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SUMMARY

Since there is a dearth of flight vibration data and because of the current wide interest in solid-propellant rockets, flight vibration data have been obtained from five vertical test shots of Shotput, the launch vehicle for vertical tests of the 100-foot inflatable sphere. The two-stage vehicle, called Shotput, consisted of a Pollux and two Recruit rocket motors as the first stage and an ABL X-248 rocket motor as the second stage. High vibration levels were obtained near burnout of the second stage of Shotput I, II, and V, whereas only low vibration levels were noted on Shotput III and IV. The peak flight vibration levels on Shotput I, II, and V occurred in the longitudinal direction at a frequency of about 570 cps and were ±40g, ±45g, and ±24g, respectively. It was found that the flight vibration levels in the normal and transverse directions were considerably less than those in the longitudinal direction. High longitudinal vibration levels were also noted during some of the ground tests of the final stage and are believed to result from a burning instability coupled with the longitudinal acoustical resonance of the rocket motor.

INTRODUCTION

In order to insure the reliable operation of space payloads, it is necessary to determine the vibrational environment of the payload. The most severe vibrational environments often occur during the launch phase of flight and are caused by buffeting, engine rough burning, and noise. Since such vibration data are almost nonexistent, it is necessary to equip vehicles with accelerometers during early phases of the developmental program to determine the vibrational environment of the payload and, if possible, to establish the cause of excessive vibration.

Vibration measurements were therefore made during the Shotput developmental phases of Echo. Echo I (1960 Iota) is the 100-foot inflatable, aluminum-coated Mylar sphere which was placed in earth orbit on August 12, 1960. Echo I was the first payload for Delta, a three-stage rocket vehicle consisting of a Thor, an Aerojet-10, and an ABL X-248. As part of the functional tests on the inflation characteristics of the sphere, a two-stage vehicle called Shotput, consisting of a Pollux XM-33E6 rocket motor with two Recruit rocket motors as the first stage and an ABL X-248-A5 as the final stage, was developed by Langley Research Center. The final stages of Shotput and Delta were identical as to payload, adapters, and fittings. Thus, the data obtained during the Shotput flights are directly applicable to the Delta vehicle used for the Echo launching, and, in general, to other rocket vehicles which use the X-248 rocket motor, such as Javelin, Argo, and Scout, and to other payloads, such as Pioneer V (1960 Alpha) and Tiros I (1960 Beta).

The purpose of this paper is to present the flight vibration data measured during the five Shotput flights. The vehicle is described and typical time histories of flight performance are given.

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DESCRIPTION

A photograph of the Shotput vehicle on its launcher at NASA Wallops Station is shown as figure 1. The general arrangement of the vehicle is given in figure 2. The first stage consists of a Pollux XM-33E6 solid-propellant rocket motor with two Recruit rocket motors at its base. Canted fins are used to spin-stabilize the vehicle. The second stage, including the spin table, is essentially the same as the final stage of Delta and consists of an ABL X-248-A5 solid-propellant rocket motor, telemeter, and payload. Despin is accomplished with the aid of three 0.6 KS 40 modified Pet rocket motors. Pertinent data for the solid-propellant rocket motors are included in figure 2. A photograph of the payload, telemeter, X-248 rocket motor, and spin table mounted on the dynamic balance machine at NASA Wallops Station and details of the final stage are shown in figure 3. The X-248 rocket motor is attached to the spin table by a Marman band held by explosive bolts in the same manner as the payload is held to the X-248. The payload container uses a linear shape-charge to separate the halves of the payload container and to allow the 100-foot sphere to inflate. The diameter of the payload container is 26.5 inches. Inflation of the sphere is accomplished by the use of subliming powder; 10 pounds of benzoic acid provided initial inflation and 20 pounds of anthroquinone provided sustaining inflation.

INSTRUMENTATION

An 8-channel telemeter (FM/AM) was used on Shotput with the quantities assigned to each channel as listed in table I. The frequency-response curve for all channels is flat to a frequency of 120 cps as shown in figure 4. This telemeter differed from the telemeter on the

Delta vehicle in that the telemeter on the Delta vehicle used the conventional FM/FM system.

The instrumentation used for obtaining the flight vibration data for Shotput I consisted of three accelerometers with natural frequencies of 280 cps and 0.65 critical damping oriented in such a way that accelerations could be measured in three mutually perpendicular directions. The nominal rating of the accelerometers used was ±40g, although the accelerometers were found to be linear to a 25-percent overload. The locations of these accelerometers are indicated in figure 5 in the center of the telemeter tray. The fourth accelerometer shown in the figure is a low-frequency instrument, rated at -3g to 13g, and is used for measuring the longitudinal acceleration time history during the flight.

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The frequency-response curve for the accelerometers is given in figure 4. Unfortunately, the available telemetry and compatible accelerometers had limited frequency response. Although the curve for the telemeter channel was flat to a frequency of only 120 cps and the curve for the accelerometer response was flat to a frequency of only 160 cps, usable data for frequencies of over 600 cps were obtained by applying amplitude corrections based on the curves of figure 4. The overall amplitude correction is the product of the two corrections and is also shown in figure 4. For example, at a frequency of 570 cps the correction factors were 0.305 for the telemeter and 0.255 for the accelerometers; these factors result in an overall correction factor of 0.078. No additional correction was necessary for the galvanometer elements used in recording the accelerations since the frequency-response characteristics of these galvanometers were flat to a frequency of 600 cps.

On Shotput II, III, IV, and V the lateral and transverse accelerometers having a range of 40g to -40g were replaced with accelerometers having a lower range for making steady-state measurements. Thus, oscillatory accelerations were recorded only in the longitudinal direction for Shotput II, III, IV, and V.

FLIGHT TIME HISTORY

It is appropriate to mention the flight time history of Shotput as a reference for the flight vibration data. Typical time histories of longitudinal steady-state acceleration, roll rate, velocity, and altitude are shown in figure 6. The data presented are intended to represent only approximately all five flights since there were some programed differences in the various flights. Actual firing times for the five vehicles are given in table II. As indicated in figure 6, after the first stage of the vehicle is ignited the canted fins of the vehicle cause it to roll. As the velocity increases, the roll rate is also increased. A coasting period follows. Toward the end of the coasting period, the nose fairing is ejected. After ejection, despin rockets on the spin table fire to decrease the rotational frequency of the final stage of Shotput to the speed predicted for the final stage of Delta. Final-stage firing and separation occurs almost simultaneously and the X-248 burns for approximately 40 seconds. Then another set of despin rockets on the telemeter tray is fired to decrease the rotational frequency to approximately zero and the payload is separated. Retro-rockets are then fired which slow down the expended X-248 rocket motor to allow sufficient distance for inflation of the 100-foot sphere (Echo). Inflation occurs after the firing of the linear shape-charge which separates the two halves of the payload container.

RESULTS AND DISCUSSION

The flight vibration data for Shotput I are listed in table III. Flight vibration data for all flights are given in figures 7 and 8. Shown in figure 9 is a sample oscillograph record which indicates the large sinusoidal accelerations observed during burning of the X-248 rocket motor.

The amplitude of the vibratory accelerations for the first 44 seconds of flight are given in figure 7. At ignition of the Pollux and the two Recruit rocket motors, oscillations occur at frequencies between 75 and 85 cps at acceleration levels ranging from ± 1g to ± 2.5g. During burning of the Pollux motor, there appeared to be only low-level random vibration and no substantial sinusoidal vibrations occurred. It may be recalled from figure 4 that amplitudes of vibrations at the higher frequencies are greatly attenuated as a result of limitations of the telemeter and transducers; hence, if significant vibration levels at higher frequencies were present, they were not detected. A few seconds after burnout of the Pollux, a weak oscillation occurred at a frequency of 170 cps for a period of about 2 seconds. (See fig. 7.) The vibration levels varied from ± 1g to ± 1.7g. During the rest of coasting flight, essentially no vibrations were recorded.

At ignition of the X-248 rocket motor and during the first 0.3 second thereafter, the signal-to-noise ratios of the telemetered signals were so low that no intelligible information was obtained concerning the shock and vibration environment during initial burning. During the next 30 seconds of sustained burning of the X-248 rocket motor, some nonperiodic oscillations occurred at a low level of acceleration of the order of $\pm\frac{1}{2}$g. During three of the five flights of the X-248 rocket motor, high-level, primarily sinusoidal, oscillations occurred as indicated in figure 8. As may be noted, both the amplitudes and time durations of the oscillations varied for each flight. The maximum vibration of ±45g occurred during the flight of Shotput II at a frequency of 570 cps at 4.1 seconds before burnout of the X-248. The maximum oscillatory acceleration for Shotput I, ±40g, was almost as high and occurred at a frequency of 570 cps at 9.3 seconds before burnout. The maximum vibration level for Shotput V was ±24g; it occurred at a frequency of 570 cps at 6.2 seconds before burnout. Burnout of the rocket motor is here defined as the time at which the pressure within the X-248 case decreased from its nominal burning pressure of about 250 lb/sq in. abs to 10 lb/sq in. abs. A plot of the nominal thrust and internal pressure is given in figure 10.

The duration of these oscillations varied considerably. The sinusoidal oscillation of Shotput I occurred over a period of about 5.1 seconds, whereas for Shotput II, the sinusoidal oscillations lasted about 1.4 seconds, and for Shotput V, the oscillations lasted about 1.2 seconds.

A sample oscillograph record for the longitudinal accelerometers on Shotput is shown in figure 9. The top trace in each group of three is the signal proportional to longitudinal vibration and the middle trace is the 0.01-second timer signal. The bottom trace is a reference line. These telemetered data indicate that bursts of sinusoidal oscillations occurred just prior to the sustained sinusoidal oscillation.

Thus, the data show that some X-248 rocket motors have high vibration levels for various lengths of time. This observation is in agreement with the results of some static firings, conducted by the U.S. Naval Research Laboratory for the National Aeronautics and Space Administration, in which four rockets were statically fired while enclosed by baffles to alleviate acoustical coupling. During two of these four firings, high vibration levels occurred at a frequency of about 600 cps near burnout of the rocket motors. During another firing, moderate vibrations occurred near burnout of the rocket motor, also at frequencies of about 600 cps. During firing of the fourth rocket motor, no high vibration levels occurred. In addition to the vibrations at about 600 cps, other frequencies obtained from these and additional ground static firings (ref. 1) and from flight data (refs. 2 and 3) have indicated resonant burning frequencies of the X-248 rocket motor in the range from 2,000 to 7,000 cps in the first 20 seconds of burning. Thus, it appears that these frequencies are a function of volume inside the rocket motor.

An effort was made in the laboratory to determine possible causes of the high excitation of the payload at a frequency of 570 cps by the X-248 rocket motor. Natural frequencies of an expended X-248 rocket motor were determined. With an electromagnetic shaker attached to the nose of the rocket motor, the predominant resonant "breathing" frequency was found to be 445 cps. When excited with an acoustic horn pointed into the nozzle of the rocket motor, the predominant resonant frequency was found to be 475 cps. Since these frequencies would probably differ from those obtained if the motor were hot and pressurized as in flight, calculations were made to determine the natural frequency of the gas in the rocket-motor chamber under conditions simulating those near burnout. The expression for natural frequencies for a gas in a cylinder is given in reference 4 as

$$\nu = \frac{c}{2}\sqrt{\left(\frac{n_z}{l}\right)^2 + \left(\frac{\alpha_{mn}}{a}\right)^2}$$

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where ν is frequency in cps, c is speed of sound, l is length of cylinder (rocket motor), a is radius of cylinder, n_z is 0, 1, 2, 3, . . . depending on longitudinal mode, and α_{mn} is the numerical value depending on radial and tangential mode. For the first tangential mode $\alpha_{10} = 0.5861$ and for the first radial mode $\alpha_{01} = 1.2197$. Values of α_{mn} for the higher modes may be found in table 5 of reference 4. The speed of sound in the burning rocket motor was estimated at 3,400 ft/sec. The lowest natural frequencies for the longitudinal, tangential, and radial modes are calculated to be 566 cps, 1,310 cps, and 2,765 cps, respectively, for the rocket motor at burnout. Thus, the excitation noted in the flights and the ground firings is probably caused by a burning instability of this rocket motor in resonance with the longitudinal acoustical mode of the contained combustion products.

In order to define the vibration environment to which a payload will be subjected, it is necessary to determine the oscillatory output force of the rocket motor. In an attempt to determine the oscillatory force necessary to cause the in-flight measured vibrations on the Shotput payload, "effective mass" (apparent-weight) measurements were made (ref. 5). The method used to obtain these measurements consisted of driving the payload through a force gage with a vibration exciter. The force was held constant and vibratory accelerations were measured at the base of the payload. The ratio of force to acceleration indicated the effective mass of the payload. A sample of these measurements for the payload of Shotput III is shown in figure 11. For Shotput III and IV, these measurements indicated that, at a frequency of 570 cps, the effective mass of the payload was equivalent to 7 and 11 pounds, respectively. The product of effective mass and the measured flight vibratory accelerations in g units indicates the approximate oscillatory output of the X-248 rocket motor. Thus, an oscillatory force output of 490 pounds would be necessary to excite a peak vibration of 35g on the payload of Shotput III. Measurements obtained during static firings on the thrust stand at Allegheny Ballistics Laboratory have indicated oscillatory thrust vibrations over 490 pounds at frequencies between 400 and 680 cps.

CONCLUDING REMARKS

Since there is a dearth of flight vibration data and because of the current wide interest in solid-propellant rockets, this paper has been written. The vibration environment encountered during the flights of five Shotput vehicles is described and a typical flight time history of longitudinal steady-state acceleration, roll rate, velocity, and altitude is shown.

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Flight vibration data have been obtained from five vertical test shots of Shotput, the launch vehicle for vertical tests of the 100-foot inflatable sphere. The two-stage vehicle, called Shotput, consisted of a Pollux and two Recruit rocket motors as the first stage and an ABL X-248 rocket motor as the second stage. High vibration levels were obtained near burnout of the second stage of Shotput I, II, and V, whereas only low vibration levels were noted on Shotput III and IV. The peak flight vibration levels on Shotput I, II, and V occurred in the longitudinal direction at a frequency of about 570 cps and were ± 40g, ± 45g, and ± 24g, respectively. It was found that the flight vibration levels in the normal and transverse directions were considerably less than those in the longitudinal direction. High longitudinal vibration levels were also noted during some of the ground tests of the final stage and are believed to result from a burning instability coupled with the longitudinal acoustical resonance of the rocket motor.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., October 10, 1961.

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TABLE I

QUANTITIES AND RANGES ASSIGNED TO TELEMETER FOR SHOTPUT II

Quantity	Range
Lateral acceleration, g units	-7.5 to 5
Longitudinal acceleration, g units	-40 to 40
Transverse acceleration, g units	-7.5 to 5
Longitudinal acceleration, g units	-3 to 13
Rate of roll, radians/sec	-20 to 40
X-248 chamber pressure, lb/sq in.	0 to 15
Fairing and payload separation	
Second-stage separation	

TABLE II

FIRING TIMES FOR SHOTPUT I, II, III, IV, AND V

Shotput	Time, sec, for -			
	First-stage ignition	First-stage burnout	Second-stage ignition	Second-stage burnout
I	0	27	79.73	121.10
II	0	25	89.94	128.48
III	0	26	91.34	131.80
IV	0	25	83.73	125.30
V	0	24	75.40	117.15

TABLE III

FLIGHT VIBRATION DATA FOR SHOTPUT I

Time after launch, sec	Acceleration, g units			Frequency, cps			Remarks
	Longitudinal	Transverse	Normal	Longitudinal	Transverse	Normal	
0 to 0.4	±2.3	±1.1	±1.9	85	85	85	
27	(a)	(a)	(a)	(b)	(b)	(b)	Burnout of Pollux.
32	(a)	(a)	(a)	(b)	(b)	(b)	Start of weak oscillation.
32.1 to 33.8	±1.7	±.8	±1.3	170	170	170	
34	(a)	(a)	(a)	(b)	(b)	(b)	End of weak oscillation.
111.2	(a)	(a)	(a)	(b)	(b)	(b)	Start of strong oscillation.
111.3	±9	±1	±1	570	(b)	(b)	
111.5	±11	±1	±1	570	(b)	(b)	
111.7	±31	±1.5	±1.5	570	(b)	(b)	
111.8	±37.5	±2	±2	570	(b)	(b)	
111.9	±40	±4 to ±5	±4 to ±5	570	[c]570	[c]570	
112.6	±35	±2	±2	570	(b)	(b)	
113.3	±25	±1.5	±1.5	570	(b)	(b)	
113.6	±21	±1	±1	570	(b)	(b)	
115.3	±7.5	±1	±1	570	(b)	(b)	
116.3							End of strong oscillation.

[a]Less than ±0.4g.
[b]Low-frequency (below 600 cps) random oscillations.
[c]Sinusoidal oscillation occurred in bursts.

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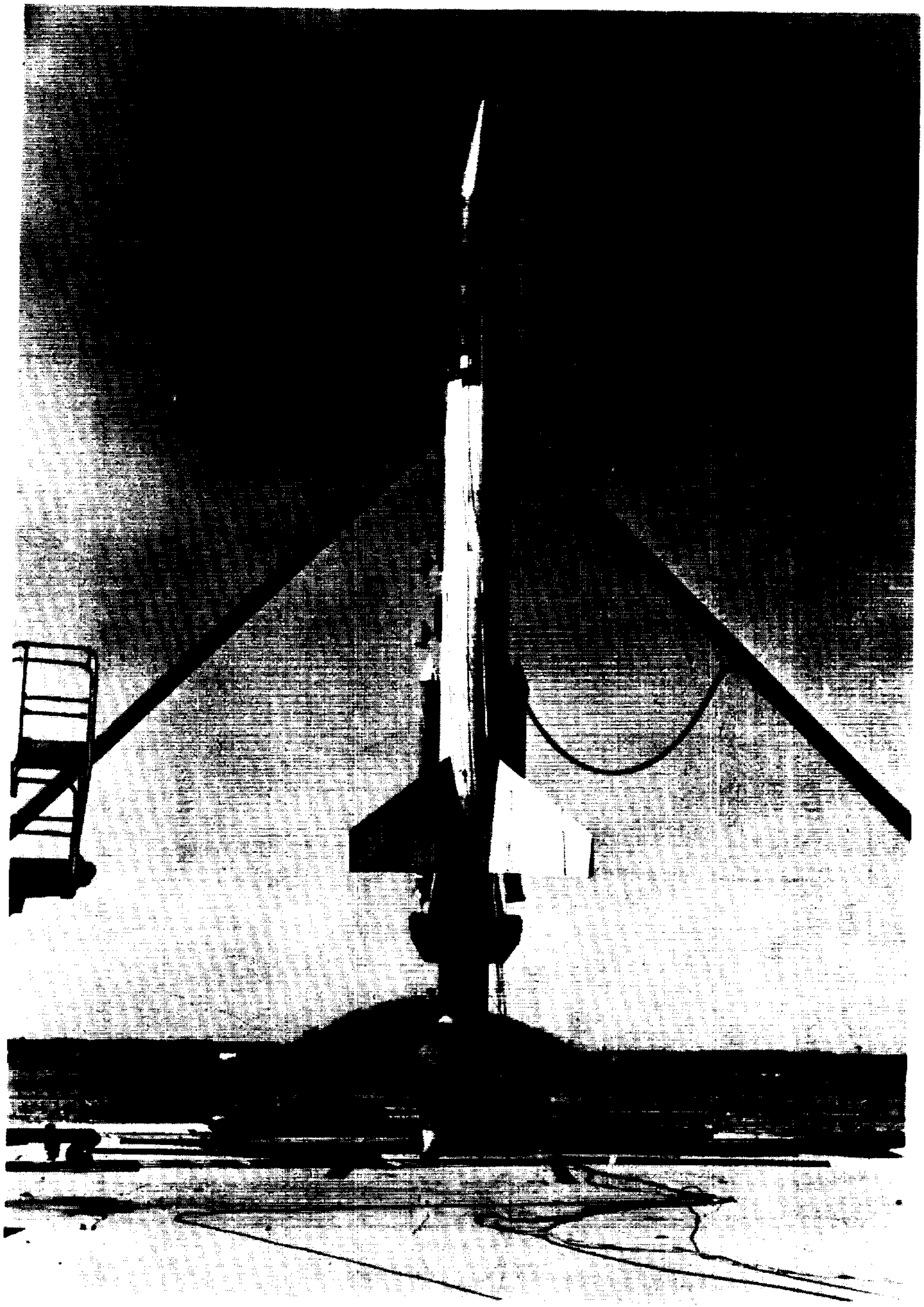

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Figure 1.- The Shotput vehicle mounted on the launcher at NASA Wallops Station.

Rocket motor	Overall length, in.	Diameter, in.	Nominal thrust, lb	Burning time, sec
0.6 KS 40 Pet	5	1.5	40	0.6
Recruit	109	11	36,000	1.5
ABL X-248	59	18	3,000	38
Pollux	233	31	50,000	23.5

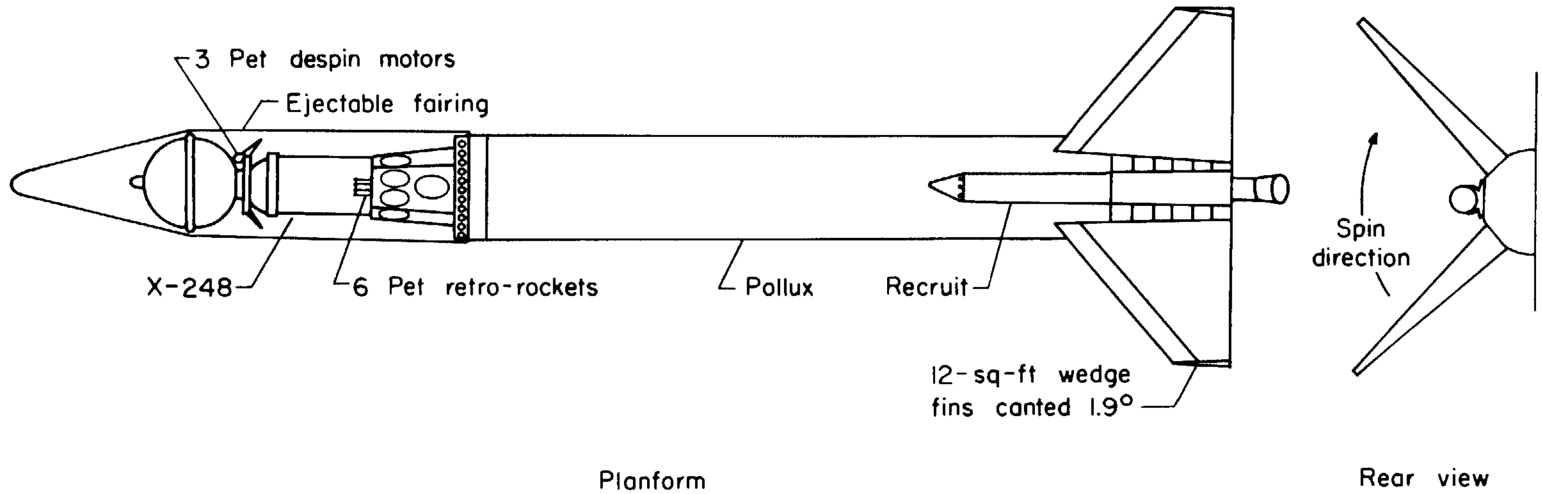

Figure 2.- General arrangement of the Shotput vehicle and information on the rocket motors.

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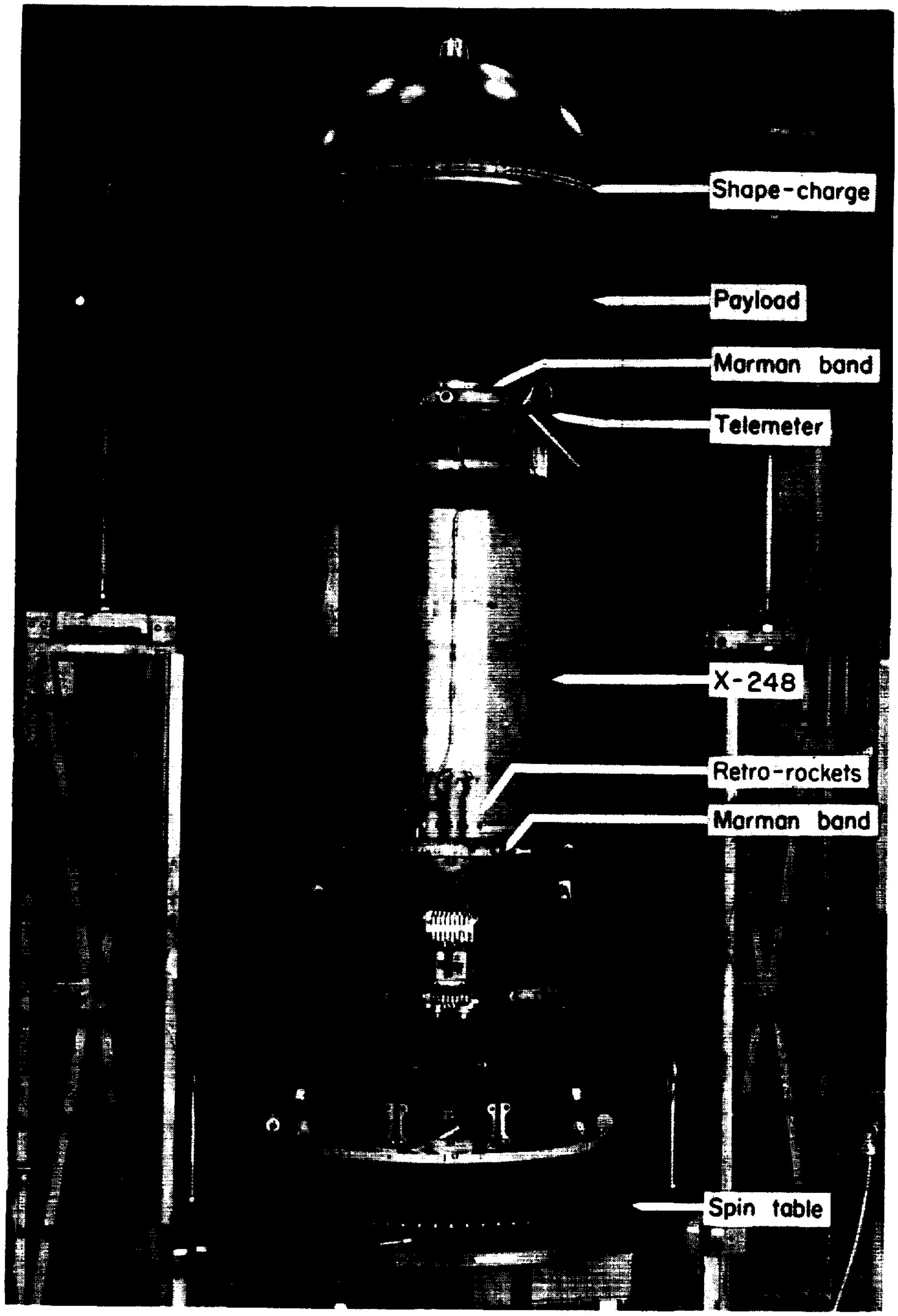

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Figure 3.- The final stage and spin-balance assembly mounted on the dynamic balance machine at NASA Wallops Station.

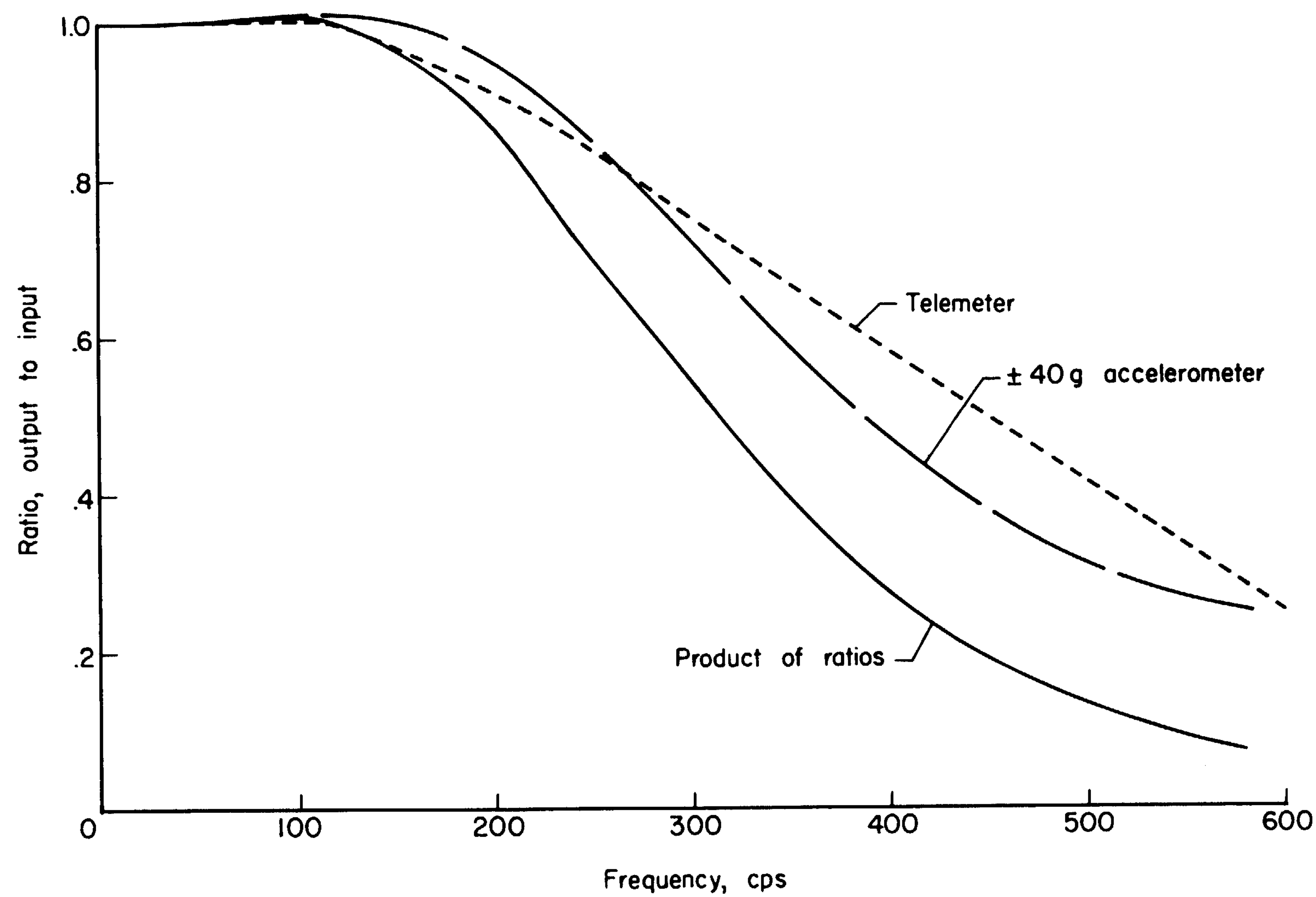

Figure 4.- Frequency-response characteristics of the telemetry and ±40g accelerometers used in Shotput.

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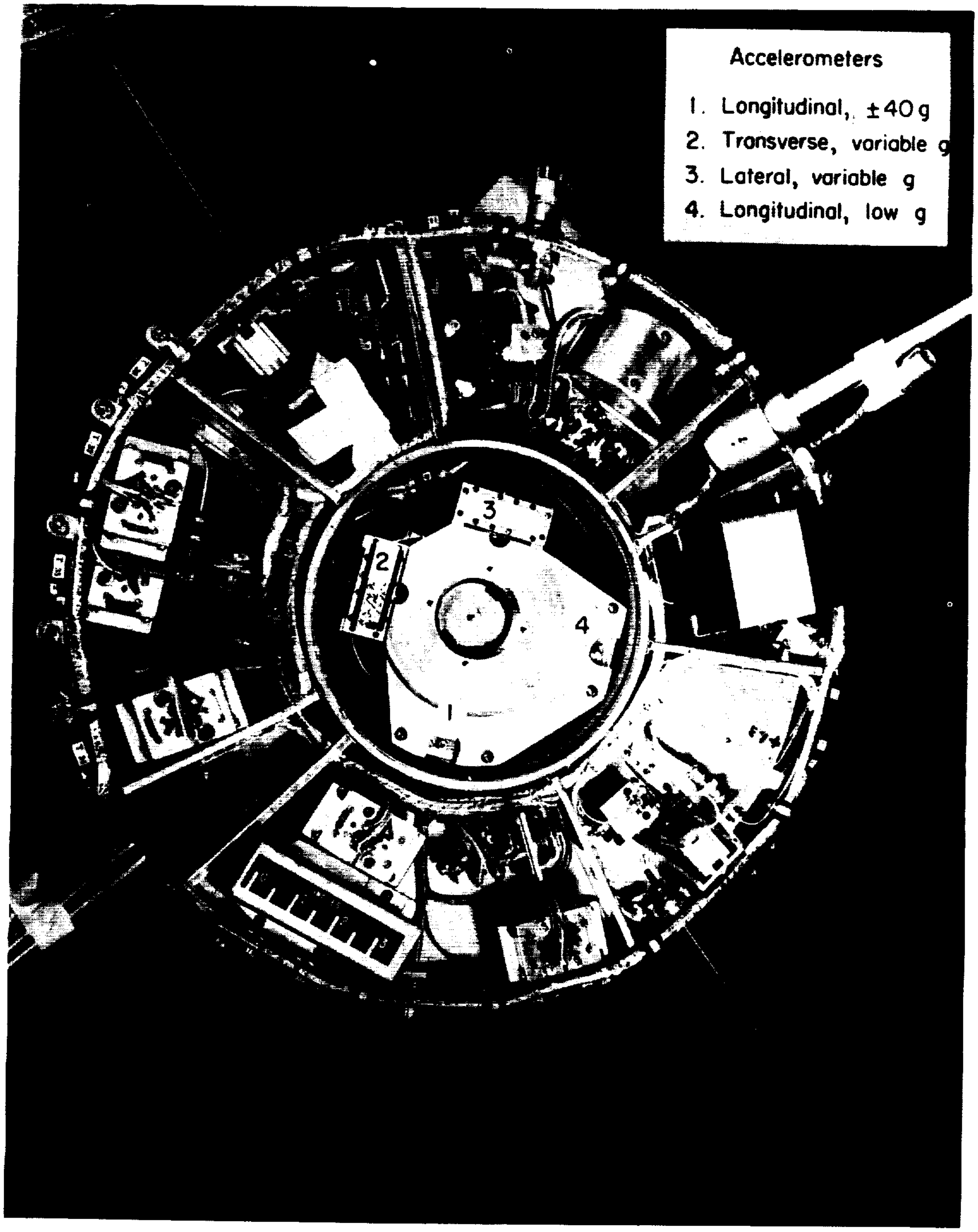

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Figure 5.- View from below of the Shotput telemetry tray which shows location of accelerometers near center of tray.

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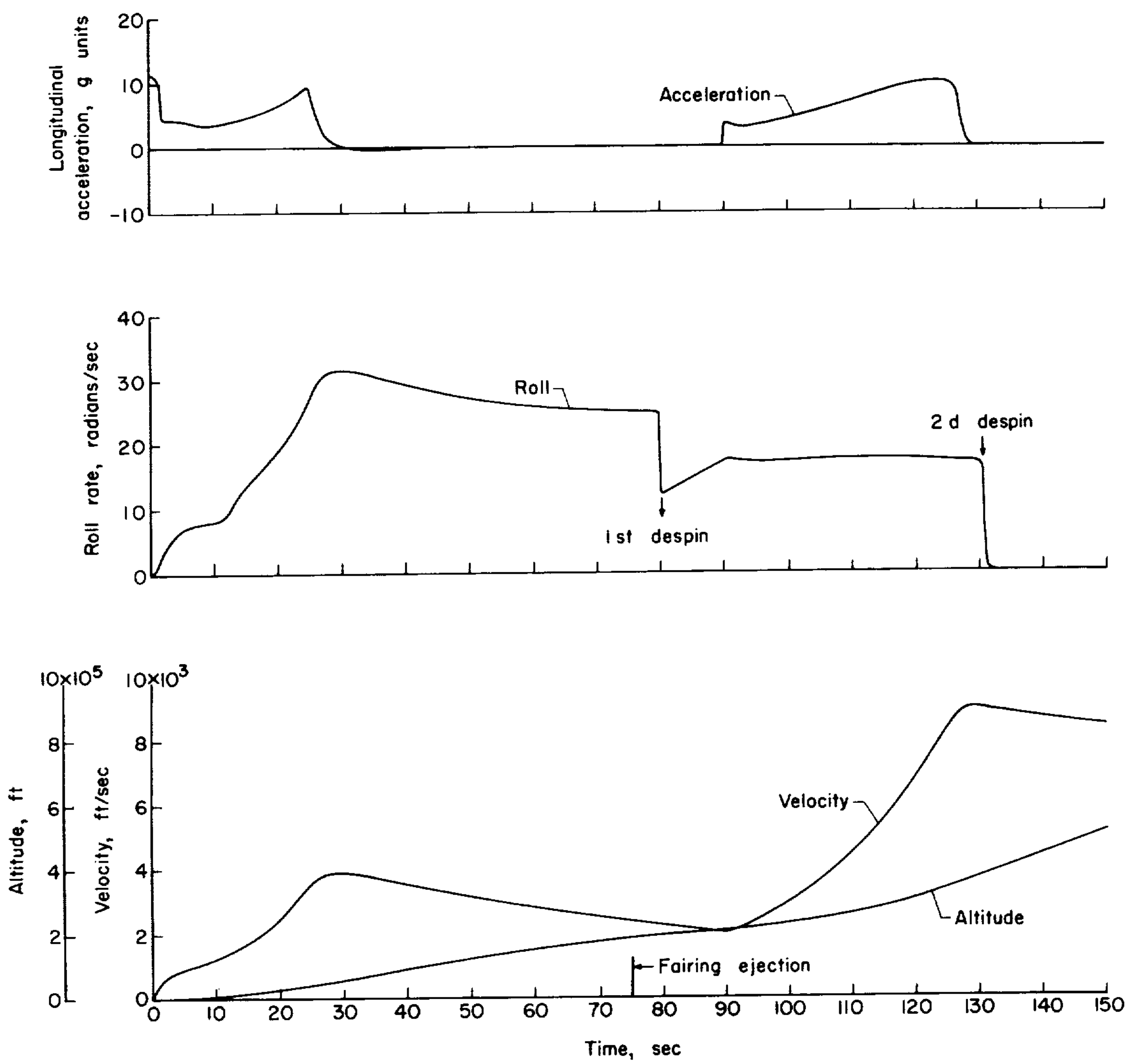

Figure 6.- Typical time histories of vehicle performance parameters.

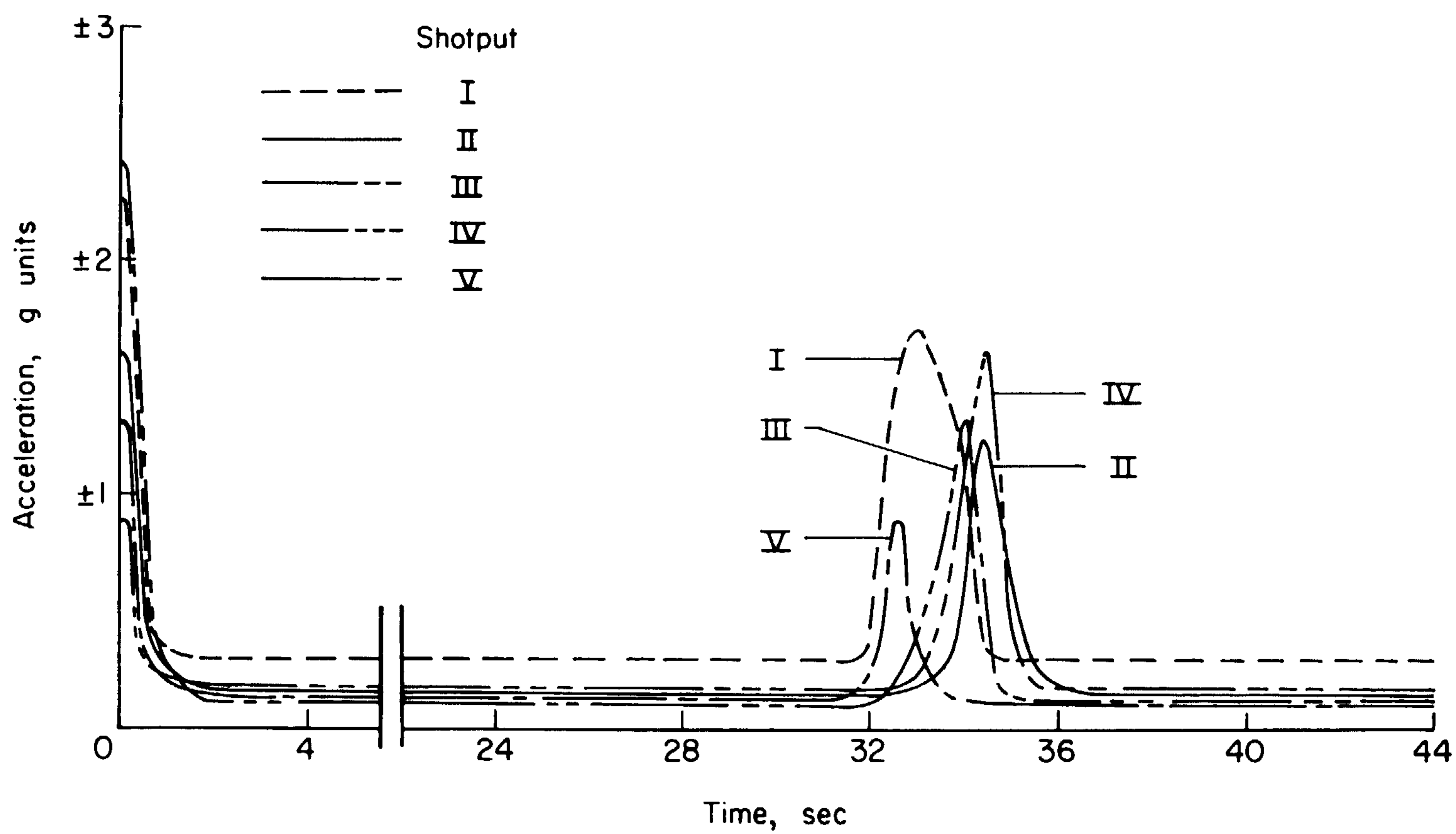

Figure 7.- Longitudinal vibrations measured at the base of the Shotput payload, obtained during the first 44 seconds of flights prior to ignition of the X-248 rocket motors.

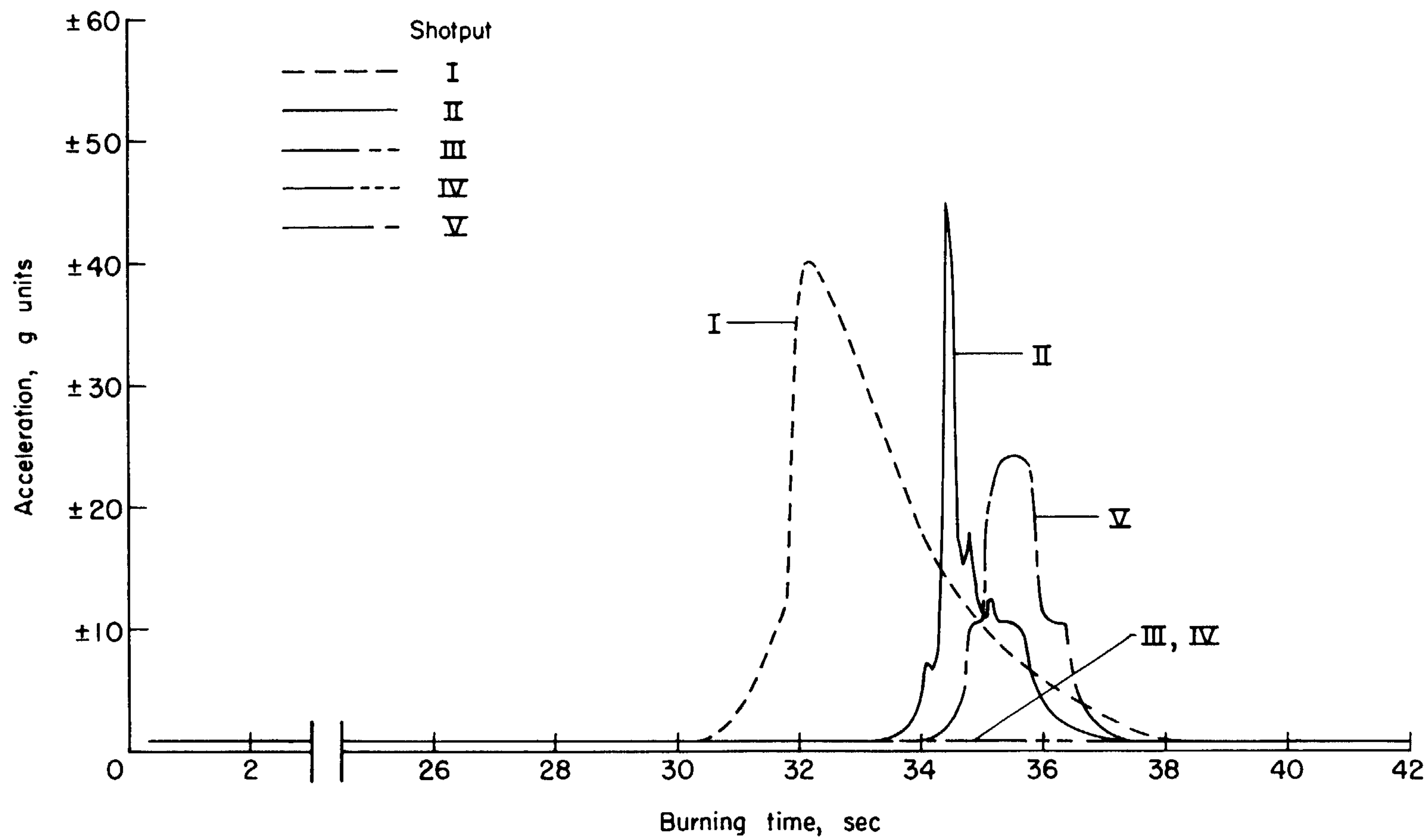

Figure 8.- Longitudinal vibrations measured at the base of the Shotput payload, obtained during the firing of the X-248 rocket motors.

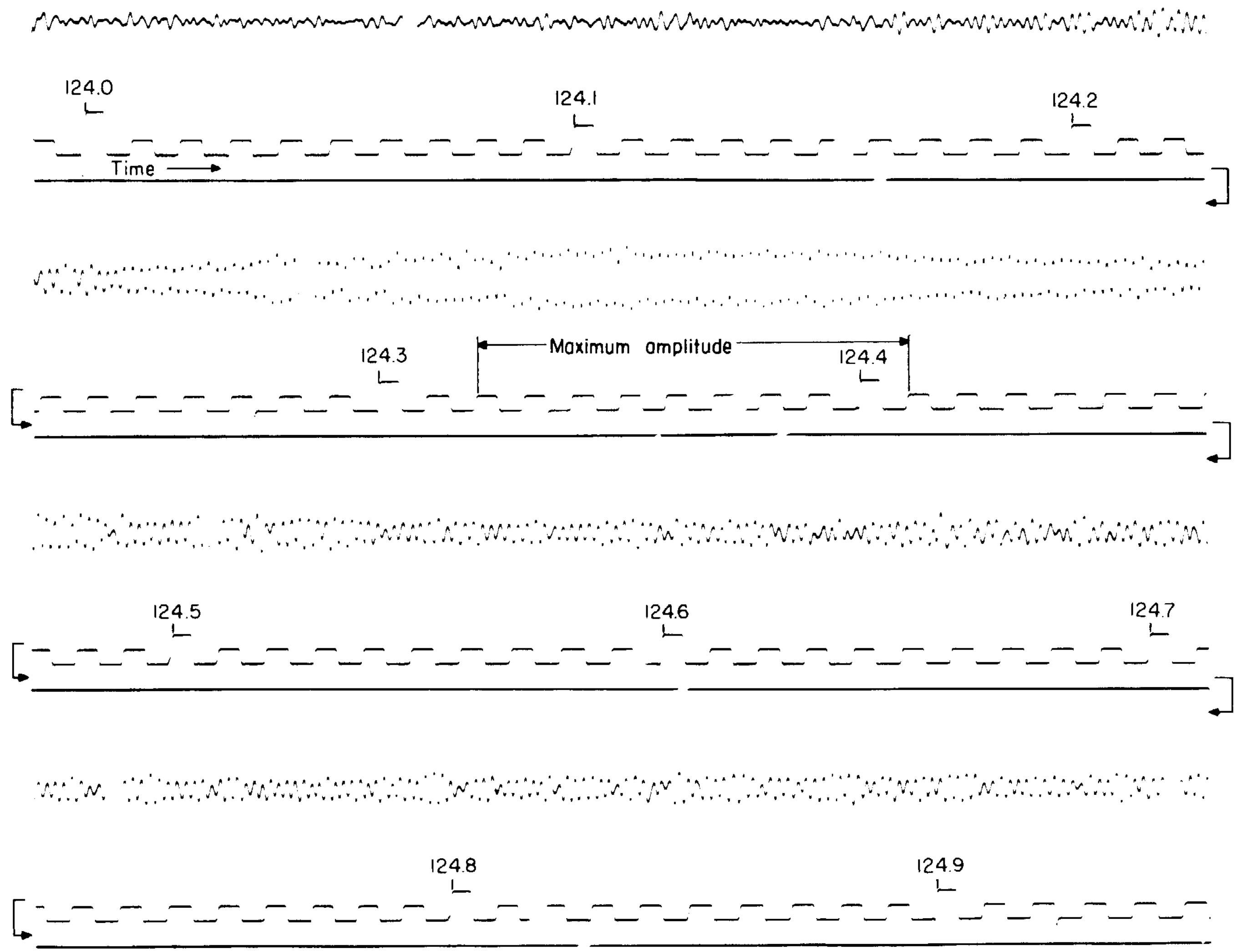

Figure 9.- Portion of telemeter record for Shotput II which shows high longitudinal accelerations at frequency of 570 cps.

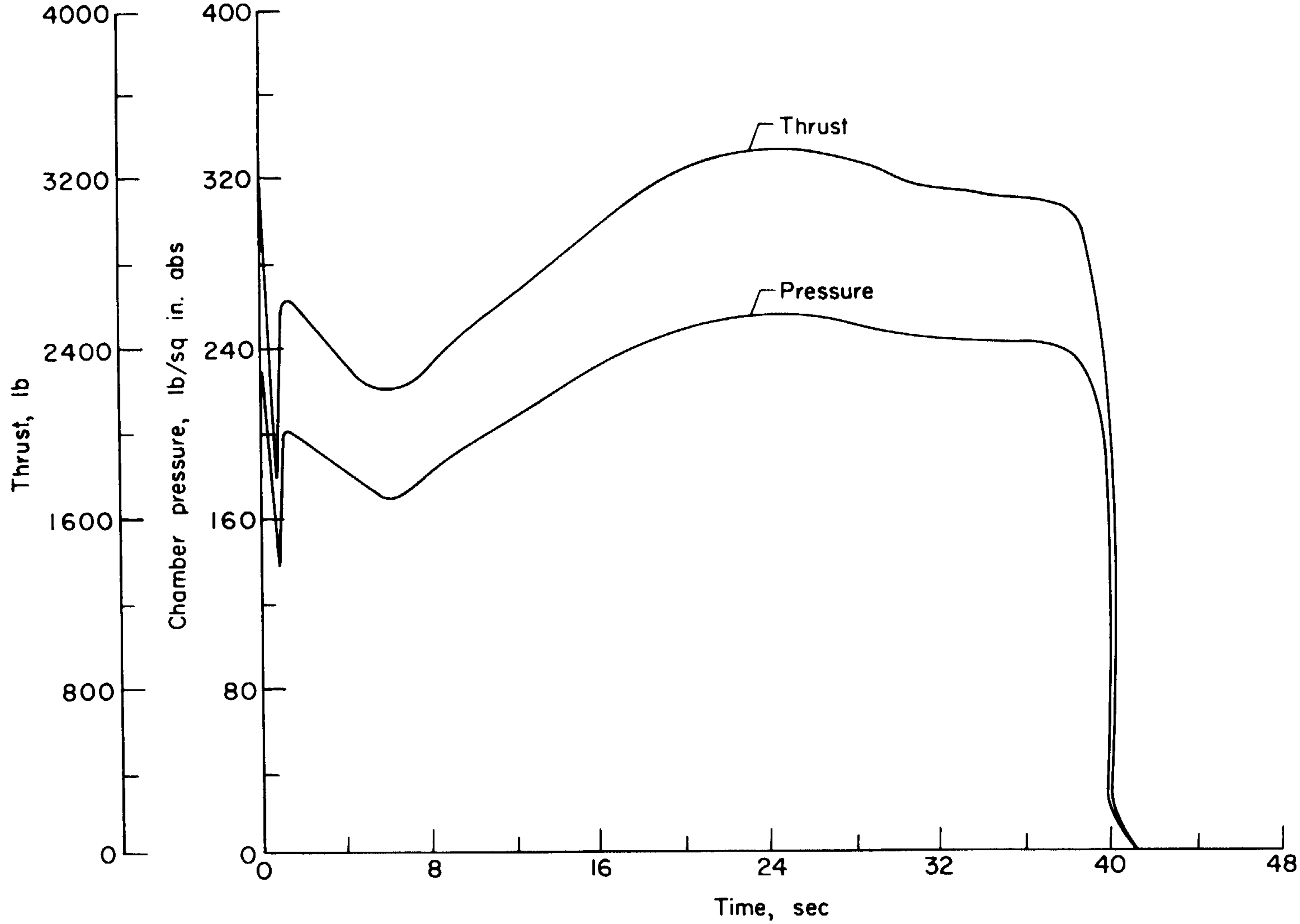

Figure 10.- Nominal chamber pressure and thrust of the X-248 rocket motor for vacuum conditions.

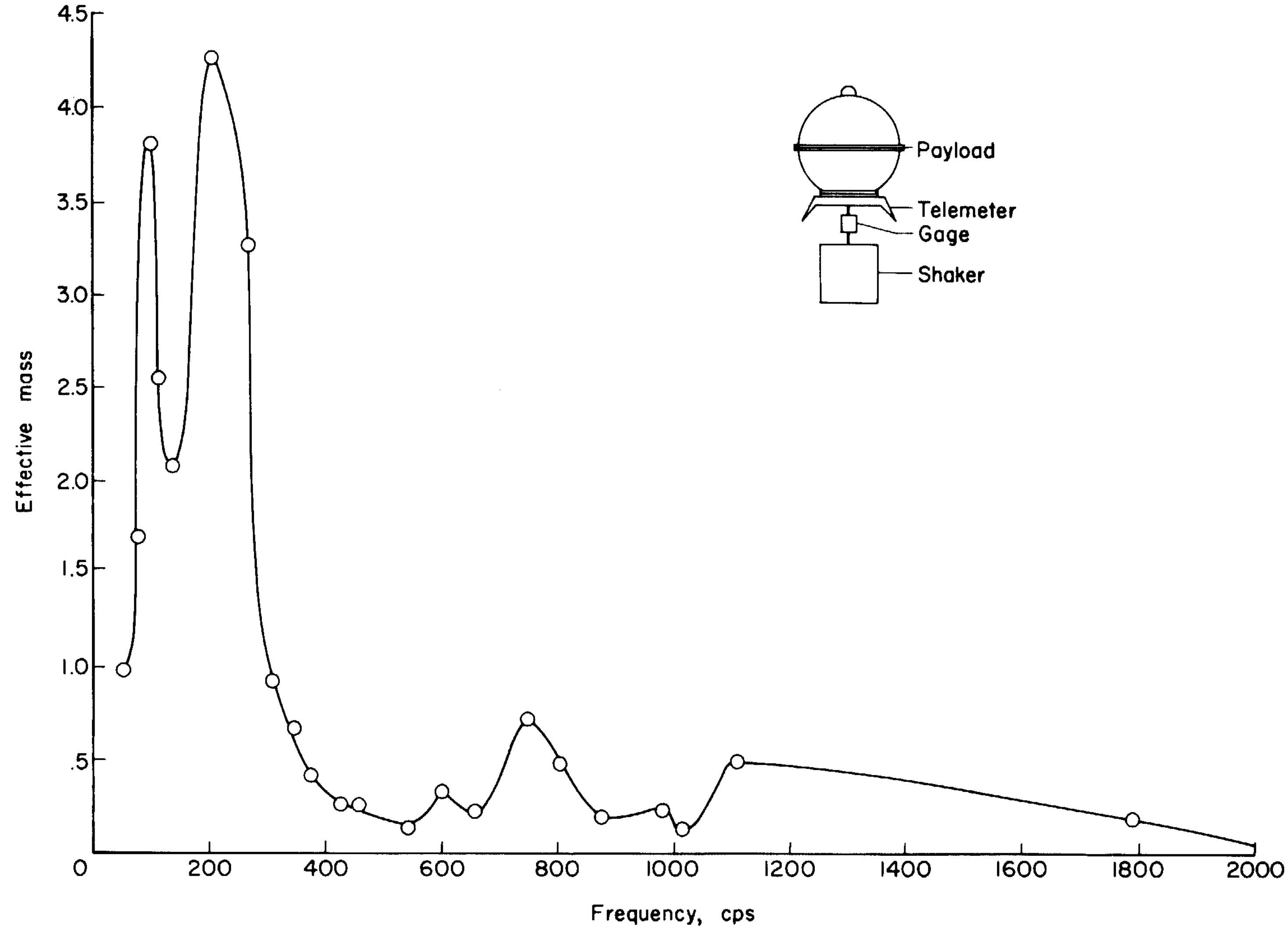

Figure 11.- Effective mass as a function of frequency for the payload and telemeter.

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